

# Decays of a Leptophobic Gauge Boson \*

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## Abstract

We discuss the theory and phenomenology of decays of a leptophobic  $U(1)_X$  gauge boson  $X$ , such as has been proposed to explain the alleged deviations of  $R_b$  and  $R_c$  from standard model predictions. If the scalars involved in the breaking of the  $SU(2) \times U(1)$  symmetry are sufficiently light,  $X$  will sometimes decay into a charged (or neutral) scalar along with an oppositely-charged  $W$  (or  $Z$ ). These decay modes could yield clean signals for the leptophobic gauge bosons at hadron colliders and provide an interesting window into the Higgs sector of the theory.

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# 1 Introduction

Several recent papers propose the existence of a gauge boson  $X$  that couples to quarks but not leptons [1, 2, 3, 4]. Such a boson could explain certain deviations from the standard model reported at LEP. The  $X$  boson, even if quite light, may have escaped detection because its decay into quark-antiquark has a large QCD background [5]. We focus on the model of reference [4] and suggest the possible detection of the  $X$  boson via its decay into  $W$  or  $Z$  bosons plus scalars decaying into heavy quarks. A search for these decay modes could provide evidence for leptophobic gauge bosons produced at hadron colliders.

## 2 The Model

The gauge group is the standard model  $SU(2) \times U(1)$  supplemented by a  $U(1)_X$  that does not act on the lepton fields. Left-handed quark doublets carry  $U(1)_X$  quantum number  $q_Q$ , right-handed  $U$  quarks  $q_U$ , and right-handed  $D$  quarks  $q_D$ . If the  $SU(2)$  symmetry breaking is done by fundamental Higgs bosons then, in general, three Higgs doublets are needed to generate quark and lepton masses. Their Yukawa couplings have the form:

$$\overline{Q} h_U \tilde{H}_U U + \overline{Q} h_D H_D D + \overline{L} h_L H_L E , \quad (1)$$

where the  $h_j$  are Yukawa coupling matrices and  $\tilde{H} = -\sigma_2 H^*$ . It follows that the  $U(1)_X$  quantum numbers of the doublets (which have weak hypercharge is  $\frac{1}{2}$ ) are

$$q(H_U) = q_U - q_Q , \quad q(H_D) = q_Q - q_D , \quad q(H_L) = 0 . \quad (2)$$

For special values of the  $q_j$ 's, it is possible to give mass to quarks and leptons with only two Higgs doublets, but none of these special choices were favored in the analysis of reference [4]. Thus we assume that<sup>1</sup>

$$0 \neq q_U - q_Q \neq q_Q - q_D \neq 0 . \quad (3)$$

If electromagnetic gauge invariance is to be left unbroken, the Higgs doublets may be written in the form:

$$H_j = \begin{pmatrix} \xi_j^+ \\ (\xi_j^0 + i \pi_j^0 + v_j)/\sqrt{2} \end{pmatrix} \quad (4)$$

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<sup>1</sup>Note that this rules out some otherwise interesting possibilities, such as the  $\eta$ -model of [3].

for  $j = U, D$ , or  $L$ . With an appropriate choice of phases for the  $H_j$  fields, their VEVs  $v_j$  may be made real and positive.

For simplicity, and because this is what was assumed in [4], we assume that the symmetry breaking is done primarily by the VEVs of the  $U$  and  $D$  doublets, and that the VEV of the  $L$  doublet is negligible,  $v_L \ll v_U, v_D$ . The extra  $U(1)_X$  couplings lead to gauge anomalies, so that additional fermion states must be introduced to cancel them. This is discussed, for example, in [4].

The relevant interaction arises via the Higgs mechanism from the kinetic energy terms of the  $H_U$  and  $H_D$  doublets:

$$D^\mu H_U^\dagger D_\mu H_U + D^\mu H_D^\dagger D_\mu H_D \quad (5)$$

where

$$D^\mu = \partial^\mu + ig_2 \frac{\vec{\tau}}{2} \cdot \vec{W}^\mu + ig_1 \frac{1}{2} B^\mu \mp ig_x (q_Q - q_{U,D}) X^\mu \quad (6)$$

and  $X^\mu$  is the new  $U(1)_X$  gauge field.

To avoid large corrections to the standard model properties of the  $Z$  we must tune the parameters of the model to make the  $X$ - $Z$  mixing small. This requires that

$$g_x^2 \left| v_U^2 (q_U - q_Q) + v_D^2 (q_Q - q_D) \right| \ll g_2^2 v^2. \quad (7)$$

Of course, the primary motivation for models of this kind is that a small amount of mixing can modify the  $Z$  couplings slightly and result in a better fit to data than the unadorned standard model. However, we are interested not in these fine details, but in the gross properties of the  $X$  boson. Therefore, we ignore mixing altogether and assume

$$v_U^2 (q_U - q_Q) + v_D^2 (q_Q - q_D) = 0. \quad (8)$$

For the same reason, we ignore mixing of the  $B$  and the  $X$  through the gauge boson kinetic energy terms, assuming that it is negligible throughout the range of energies of interest.

For (8) to be satisfied,  $q_U - q_Q$  and  $q_D - q_Q$  must have the same sign, which we take to be positive by convention. Because  $v_U^2 + v_D^2 \approx v^2$  (where  $v \simeq 246$  GeV is the VEV of the standard model), we can write

$$v_U \approx v \sqrt{\frac{q_D - q_Q}{q_U + q_D - 2q_Q}}, \quad v_D \approx v \sqrt{\frac{q_U - q_Q}{q_U + q_D - 2q_Q}}. \quad (9)$$

The contribution of the doublet VEVs to the mass of the  $X$  boson is

$$m_X^{\min} \equiv g_x v \sqrt{(q_U - q_Q)(q_D - q_Q)}. \quad (10)$$

Since there may also be  $SU(2)$  singlet scalars contributing to the  $X$  mass, (10) should be regarded as a lower bound.

In the Higgs mechanism, one linear combination of the two charged fields,  $\xi_U^\pm$  and  $\xi_D^\pm$  is transformed into the longitudinal component of the  $W^\pm$ , while a similar linear combinations of the two fields  $\pi_U^0$  and  $\pi_D^0$  becomes the longitudinal component of the  $Z$ . If the  $U(1)_X$  breaking comes entirely from the doublets, the other linear combination becomes the longitudinal component of the  $X$ .<sup>2</sup> In unitary gauge, we may set

$$\sum_{\substack{j \\ U,D}} v_j \xi_j^+ = \pi_U^0 = \pi_D^0 = 0. \quad (11)$$

In our no-mixing,  $v_L = 0$  approximation, we can take

$$H_U = \begin{pmatrix} v_D \xi^+ / v \\ (\xi_U^0 + v_U) / \sqrt{2} \end{pmatrix} \quad H_D = \begin{pmatrix} -v_U \xi^+ / v \\ (\xi_D^0 + v_D) / \sqrt{2} \end{pmatrix} \quad (12)$$

where  $\xi^+$  is the surviving combination of  $\xi_U^+$  and  $\xi_D^+$ . The  $\xi^+$ ,  $\xi_U^0$  and  $\xi_D^0$  fields need not be mass eigenstates (indeed, we expect some mixing with the components of  $H_L$ ) but for now we ignore mixing.

### 3 $X$ Decays

The couplings responsible for the decay of  $X$  into  $W$  or  $Z$  plus a scalar are obtained by putting (12) into (1):

$$\begin{aligned} & g_X g_2 \frac{v_U v_D}{v} (q_U + q_D - 2q_Q) \left( \xi^+ X^\mu W_\mu^- + \xi^- X^\mu W_\mu^+ \right) \\ & + \frac{g_X g_2}{\cos \theta} \left( (q_D - q_Q) v_D \xi_U^0 - (q_U - q_Q) v_U \xi_D^0 \right) X^\mu Z_\mu. \end{aligned} \quad (13)$$

Using (9) and  $m_W = g_2 v / 2 = m_Z \cos \theta$ , we find:

$$2 g_X \sqrt{(q_U - q_Q)(q_D - q_Q)} \left( m_W \left( \xi^+ X^\mu W_\mu^- + \xi^- X^\mu W_\mu^+ \right) + m_Z \xi^0 X^\mu Z_\mu \right) \quad (14)$$

where

$$\xi^0 \equiv \xi_D^0 \sqrt{\frac{q_D - q_Q}{q_U + q_D - 2q_Q}} - \xi_U^0 \sqrt{\frac{q_U - q_Q}{q_U + q_D - 2q_Q}}. \quad (15)$$

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<sup>2</sup>We will discuss below what happens if there is additional  $U(1)_X$  symmetry breaking.

Equation (14), our central result, is valid provided that all  $SU(2)$  breaking is done by the VEVs of  $H_U$  and  $H_D$ . Our result is unaffected by additional  $U(1)_X$  breaking due to the VEVs of  $SU(2)$  *singlet* fields. These would contribute to  $m_X$  and lead to the survival of a linear combination of the various  $\pi$  fields, but one which does not appear in (14).

Note that  $\xi^\pm$  and  $\xi^0$  form a triplet under the custodial  $SU(2)$  symmetry [6]. The orthogonal linear combination of the two neutral states is a custodial  $SU(2)$  singlet, which is the analog in this model of the standard model Higgs boson. The custodial  $SU(2)$  symmetry may be broken by the mass mixing between the neutral states or by the masses and mixing of all of the states with other spinless bosons in the model, but it remains manifest in the couplings.

The dominant decay mode of  $X$  is into quark-antiquark pairs, where the QCD background may obscure the resonance. For this reason, we are interested in the branching ratio for the decay of the  $X$  into  $W\xi$  and  $Z\xi$  due to interaction (14). If the  $\xi$ s are sufficiently light, these decays may offer clearer signatures of a leptophobic gauge boson.

For each family, the rate  $\Gamma$  for  $X$  to decay into a  $Q = \frac{2}{3}$  quark-antiquark pair is:

$$\begin{aligned}\Gamma(X \rightarrow U\bar{U}) & \\ & \approx \frac{1}{4\pi} g_X^2 (q_Q^2 + q_U^2) (1 - m_q^2/m_X^2) p(m_X, m_q, m_q) \\ & = \frac{1}{8\pi} g_X^2 (q_Q^2 + q_U^2) (1 - m_q^2/m_X^2) \sqrt{m_X^2 - 4m_q^2}.\end{aligned}\tag{16}$$

where  $p$  is the final particle momentum in the rest frame,

$$p(m_X, m_a, m_b) = \frac{m_X}{2} \sqrt{\left(1 - \frac{(m_a + m_b)^2}{m_X^2}\right) \left(1 - \frac{(m_a - m_b)^2}{m_X^2}\right)}.\tag{17}$$

For each family, the rate  $\Gamma$  for  $X$  to decay into a  $Q = -\frac{1}{3}$  quark-antiquark pair is:

$$\begin{aligned}\Gamma(X \rightarrow D\bar{D}) & \\ & \approx \frac{1}{4\pi} g_X^2 (q_Q^2 + q_D^2) (1 - m_q^2/m_X^2) p(m_X, m_q, m_q) \\ & = \frac{1}{8\pi} g_X^2 (q_Q^2 + q_D^2) (1 - m_q^2/m_X^2) \sqrt{m_X^2 - 4m_q^2}.\end{aligned}\tag{18}$$

One might expect the gauge boson decays to be suppressed by powers of  $m_W/m_X$  because of the explicit factors of  $m_W$  and  $m_Z$  in (14). However, these factors are compensated by the enhancement

from the longitudinal  $W$  and  $Z$ . Thus the partial widths for  $W\xi$ ,  $Z\xi$  and  $q\bar{q}$  decays are of the same order, differing only by kinematic and counting factors.

For the  $W^+$  decay, the square of the invariant matrix element is

$$\frac{4}{3}g_x^2(q_U - q_Q)(q_D - q_Q)m_W^2 \left( -g_{\mu\nu} + \frac{p_W^\mu p_W^\nu}{m_W^2} \right) \left( -g_{\mu\nu} + \frac{p_{X\mu} p_{X\nu}}{m_X^2} \right). \quad (19)$$

Using  $(p_X p_W) = (m_X^2 + m_W^2 - m_\xi^2)/2$ , we find

$$\frac{4}{3}g_x^2(q_U - q_Q)(q_D - q_Q)m_W^2 \left( 2 + \frac{(m_X^2 + m_W^2 - m_\xi^2)^2}{4m_X^2 m_W^2} \right). \quad (20)$$

Thus the partial width into  $W^\pm \xi^\mp$  is

$$\begin{aligned} \Gamma(X \rightarrow W^\pm \xi^\mp) & \\ & \approx \frac{1}{3\pi} g_x^2 (q_U - q_Q)(q_D - q_Q) \\ & \cdot \left( 2 + \frac{(m_X^2 + m_W^2 - m_{\xi^\pm}^2)^2}{4m_X^2 m_W^2} \right) \frac{m_W^2}{m_X^2} p(m_X, m_W, m_{\xi^\pm}). \end{aligned} \quad (21)$$

For the decay into  $Z\xi^0$ , because of custodial symmetry, the partial width is given by half of this result, with  $m_W \rightarrow m_Z$  and  $m_{\xi^\pm} \rightarrow m_{\xi^0}$ :

$$\begin{aligned} \Gamma(X \rightarrow Z\xi^0) & \\ & \approx \frac{1}{6\pi} g_x^2 (q_U - q_Q)(q_D - q_Q) \\ & \cdot \left( 2 + \frac{(m_X^2 + m_Z^2 - m_{\xi^0}^2)^2}{4m_X^2 m_Z^2} \right) \frac{m_Z^2}{m_X^2} p(m_X, m_Z, m_{\xi^0}). \end{aligned} \quad (22)$$

Branching ratios for the decay modes  $X \rightarrow W^\pm \xi^\mp$ ,  $X \rightarrow Z\xi^0$  are determined by equations (16), (18), (21) and (22). Figures 1, 2 and 3 show these branching ratios (and that of  $X \rightarrow t\bar{t}$ ) as a function of  $m_X$  for two representative leptophobic models and two values for the  $\xi$  masses. One model is that discussed in reference [4]; in the other we choose  $q_Q = 0$ , for which anomaly cancellation is more straightforward. The branching ratios for these signature modes of decay of a leptophobic gauge boson are large enough to be of experimental interest.

## 4 Phenomenology

The production cross section for  $X$  depends on  $g_x$ , which otherwise does not enter into our analysis except to determine the minimum value of the  $X$  mass,  $m_X^{\min}$ . With  $g_x = 0.15$ , one of the values

discussed in reference [4], this cross section is given approximately in figure 4. It is well below the published limit from CDF for all values of  $m_X$ . For this value of  $g_X$ ,  $m_X^{\min} \approx 90$  GeV.

The  $\xi$ 's produced in  $X$  decays decay primarily into heavy quarks, giving rise to the processes:

$$\begin{aligned} X &\rightarrow W^-\xi^+ \\ &\hookrightarrow c\bar{s} \end{aligned} \tag{23}$$

$$\begin{aligned} X &\rightarrow Z\xi^0 \\ &\hookrightarrow b\bar{b} \end{aligned} \tag{24}$$

If, as expected, the  $\xi$ 's mix slightly with the states in the  $H_L$  doublet, there will also be decay modes in which  $\tau$ 's are produced:

$$\begin{aligned} X &\rightarrow W^-\xi^+ \\ &\hookrightarrow \tau^+\nu_\tau \end{aligned} \tag{25}$$

$$\begin{aligned} X &\rightarrow Z\xi^0 \\ &\hookrightarrow \tau^+\tau^- \end{aligned} \tag{26}$$

Note also that if the  $X$  is above  $t\bar{t}$  threshold, its decay into  $t\bar{t}$  could be a significant source of  $ts$ .

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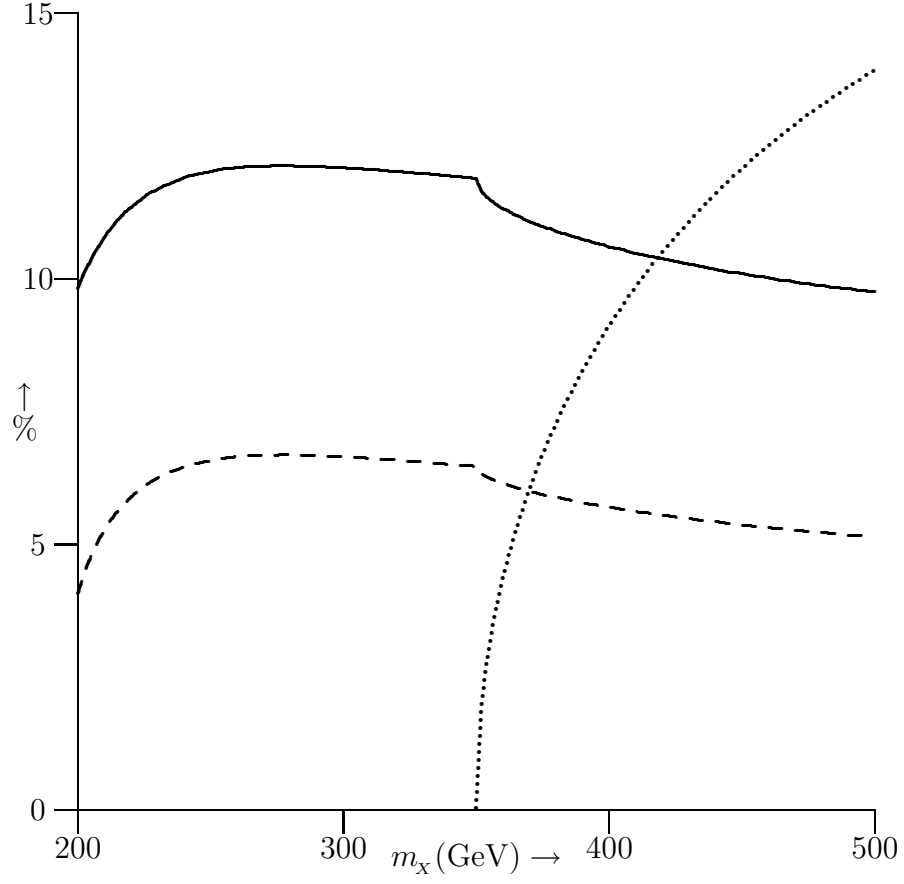


Figure 1: Branching ratios in  $X$  decay for  $(q_Q, q_U, q_D) = (-1, 2, 1)$  and  $m_{\xi^\pm} = m_{\xi^0} = 100$  GeV. The solid line is  $B(X \rightarrow W^\pm \xi^\mp)$ . The dashed line is  $B(X \rightarrow Z \xi^0)$ . The dotted line is  $B(X \rightarrow t\bar{t})$ .

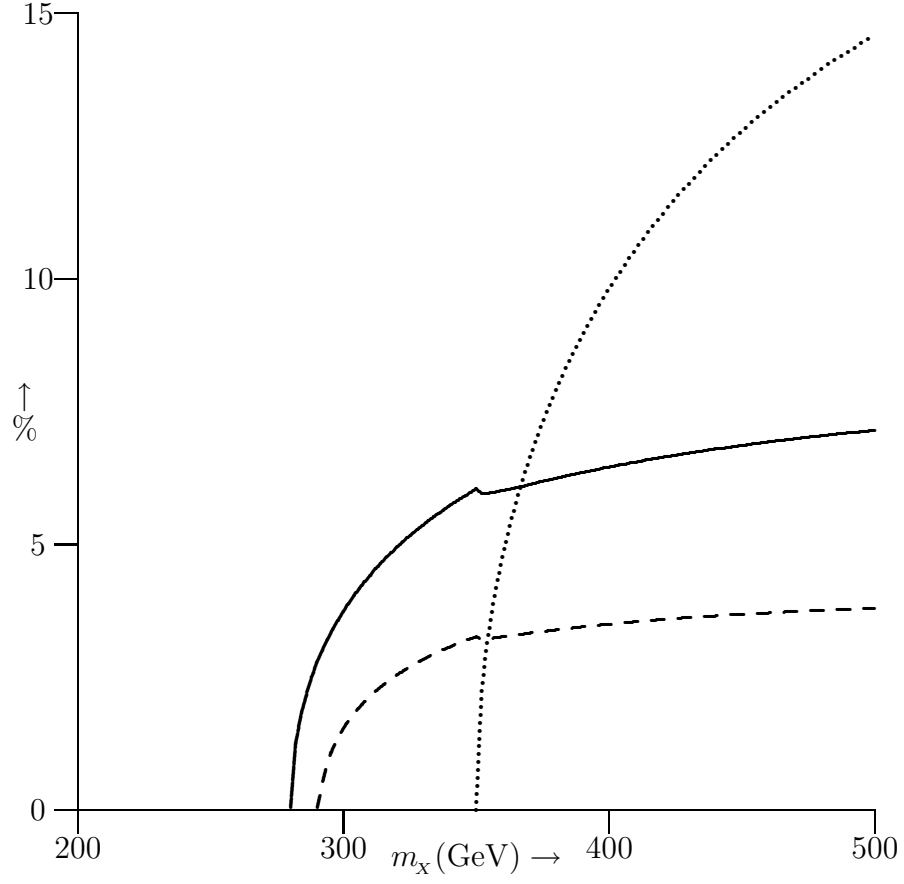


Figure 2: Branching ratios in  $X$  decay for  $(q_Q, q_U, q_D) = (-1, 2, 1)$  and  $m_{\xi^\pm} = m_{\xi^0} = 200$  GeV. The solid line is  $B(X \rightarrow W^\pm \xi^\mp)$ . The dashed line is  $B(X \rightarrow Z \xi^0)$ . The dotted line is  $B(X \rightarrow t\bar{t})$ .

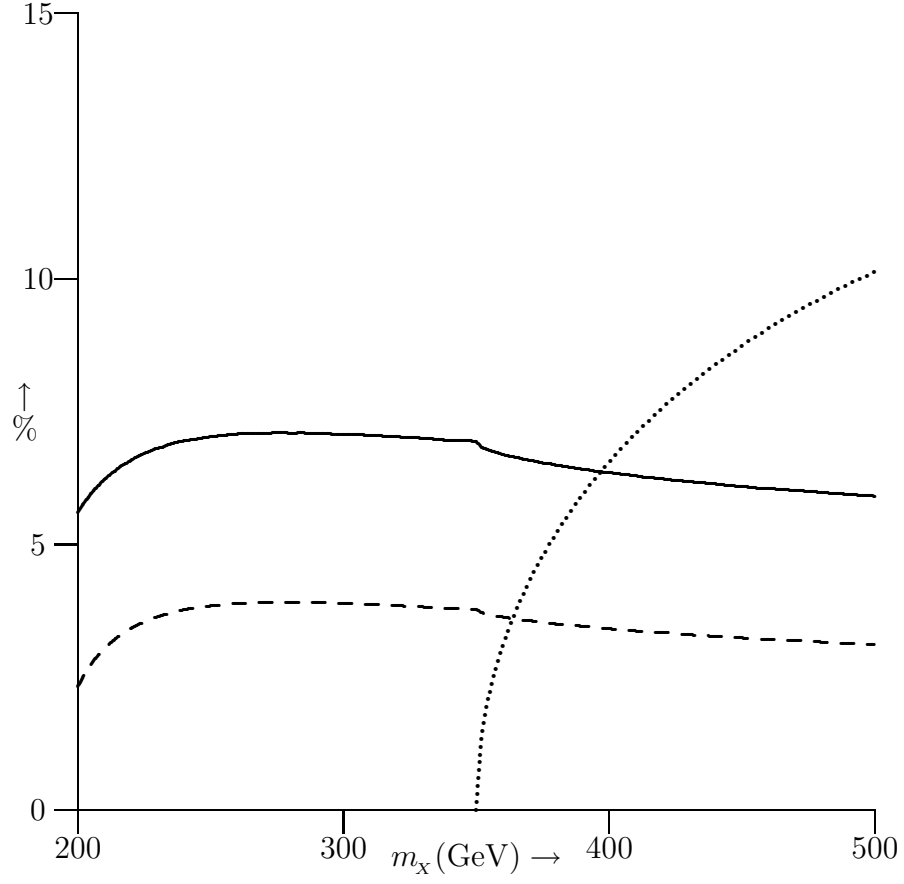


Figure 3: Branching ratios in  $X$  decay for  $(q_Q, q_U, q_D) = (0, 1, 1)$  and  $m_{\xi^\pm} = m_{\xi^0} = 100$  GeV. The solid line is  $B(X \rightarrow W^\pm \xi^\mp)$ . The dashed line is  $B(X \rightarrow Z \xi^0)$ . The dotted line is  $B(X \rightarrow t\bar{t})$ .

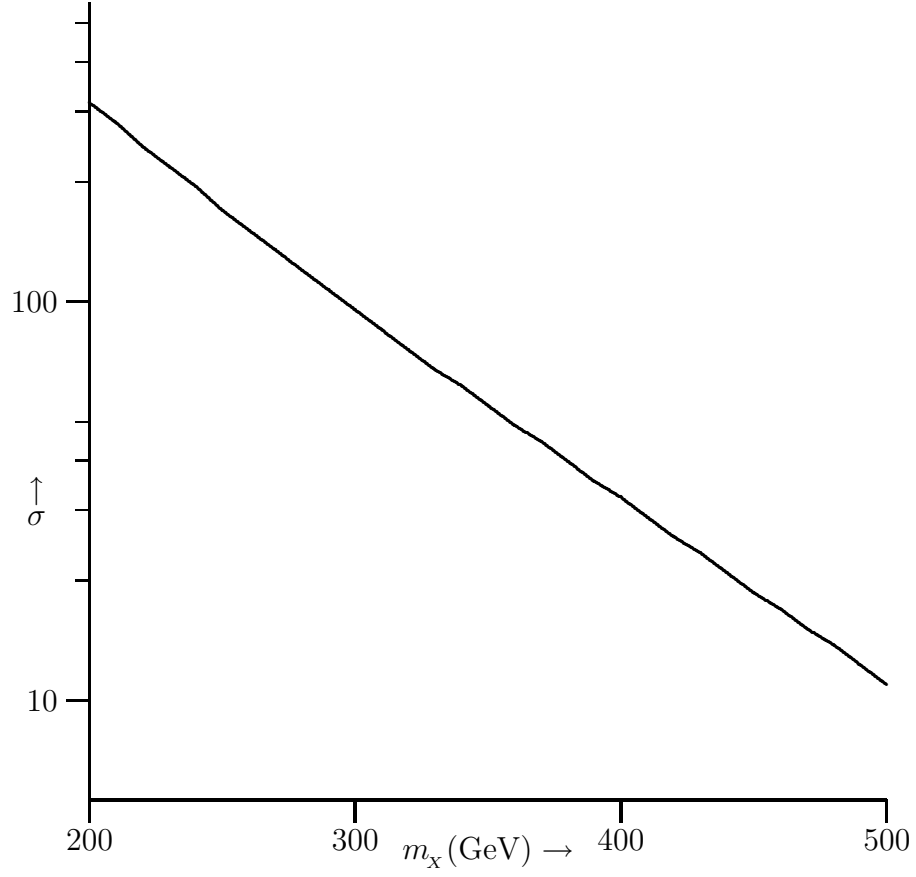


Figure 4: An estimate of the  $X$  production cross section in picobarns at center of mass energy 1800 GeV for  $(q_Q, q_U, q_D) = (-1, 2, 1)$  and  $g_X = 0.15$ .